# The Future of X-ray Spectroscopy of Galactic Black Hole Binaries

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**Abstract.** There are four major X-ray satellites currently in operation (*RXTE*, *Chandra*, *XMM-Newton*, *INTEGRAL*), with two more shortly to follow (*Astro E II*, *Swift*), and several very ambitious observatories in various stages of planning (*Constellation-X*, *MAXIM*, *XEUS*). This very rich period of X-ray observation is leading to great advances in our understanding of the accretion flow onto the black hole, although we are quickly learning (or perhaps better put, remembering) exactly how complicated this flow can be. This review was meant to assess future prospects for X-ray spectroscopy of black hole binaries; however, I first look backward to the observations and theories that helped us arrive at our current 'paradigm'. I then discuss current and near-future spectroscopic studies, which increasingly (and very fruitfully) treat X-ray spectroscopy as part of a larger, intimately connected picture along with radio, optical, and gamma-ray spectroscopy. Equally importantly, and in large part thanks to the success of *RXTE*, there is now a strong realization that spectral-temporal correlations, even across wavelength bands, are crucial to our understanding of the physics of these systems. Going forward, we are well-poised to continue to advance our knowledge via X-ray spectroscopy, both with existing satellites that have a long lifetime ahead of them (*Chandra*, *XMM-Newton*, *INTEGRAL*), and with the next generation of instruments. If there is any 'hole' in this bright future, it is the potential loss of *RXTE*, with no designated follow-up mission. Studies of multi-wavelength spectral-temporal correlations will become more difficult due to the loss of two important attributes of *RXTE*: its fast timing capabilities and its extremely flexible scheduling which has made many of these studies possible.

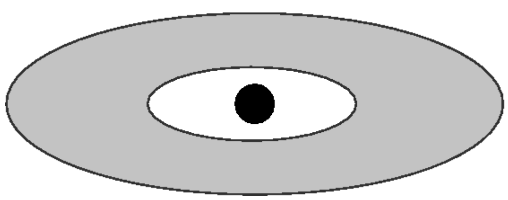

**FIGURE 1.** The spectroscopic model of accretion flows in black hole binaries, circa 1973 (e.g., Shakura & Sunyaev 1973).

## LOOKING BACKWARD

*Those who forget history are condemned to repeat it. – George Santayana*

There are a number of reviews describing theoretical models and observations of galactic black hole candidate (GBHC) binaries [e.g., 1, 2]. It is interesting to look back, however, and note that many of the components incorporated into models today had their origins some time ago, with many important insights made using very sparse data. Some ideas have come into and out of consideration several times over the past thirty years. See [2], for example, for a brief description of the history of the fluorescent Fe line in GBHC, which has gone from being interpreted as broad to narrow, and back and forth again, several times [3, 4, 5, 6, etc.]. I myself have been on both sides of this issue [7, 8], although I am certainly not alone in this regard [6, 9].

The seminal theoretical work that helped usher in the "modern era" of the study of accretion flows was that of Shakura & Sunyaev [10, see Fig. 1]. Theories, aided by observations, quickly added complexity to this basic picture. The concept of a two-phase flow (i.e., disk and 'corona') was introduced, and was even suggested to represent 'advection domination' [11, 12]. Disks were hypothesized to be warped [13], to produce magnetic flares in their inner regions [14], or to be surrounded by a hot corona that produced the characteristic spectrum of 'hard state' observations [15]. Very brief, fast-photometry optical observations [16] revived the concept of disk flares, and tied them to optical synchrotron emission [17]. Magneto-hydrodynamic turbulence was suggested as the viscous dissipation mechanism [18], and later even suggested to be acting within the innermost stable circular orbit (ISCO) [19].

A major observational advance was made when radio jets were discovered in X-ray binaries [20]. It is interesting to note, however, that 'radio jet ejection events' previously had been hypothesized, probably correctly so, based solely upon 'dipping events' in X-ray observations of GX 339−4 [21]. Meanwhile, the study of warped

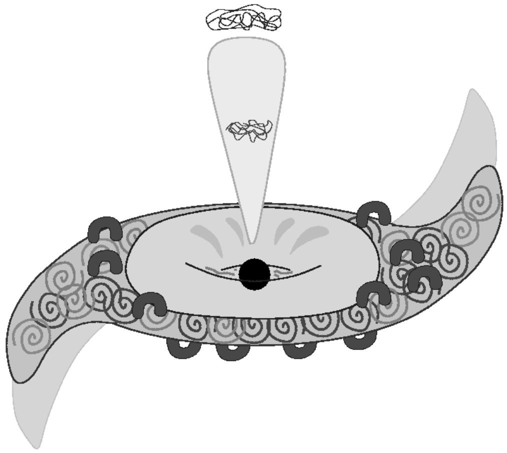

**FIGURE 2.** The spectroscopic model of accretion flows in black hole binaries, circa 2003. It is now widely believed that (starting from the outer disk, and working our way inward, then along the axis and upward) that the accretion flow consists of: a warped disk, with disk wind; MHD turbulence providing the viscosity; magnetic flaring activity and/or a corona; dissipation from the region interior to the innermost stable circular orbit; an outward propagating jet yielding radio and possibly X-ray emission; and the interaction of this jet with the surrounding interstellar medium.

disks had been revived [22], and advection dominated flows had undergone several revivals [23, 24] and further had winds, and several new acronyms, appended to them [25]. In at least one instance [26], an X-ray binary jet clear manifested itself in the X-ray due to its interaction with the interstellar medium. It also has been suggested, however, that steady jets in the hard state can significantly contribute to the observed 2-200 keV X-ray spectrum [27].

This past 30 years of research has led to a picture much as presented in Fig. 2. My own reading of our field is that most of us would agree that *all* the components shown in Fig. 2 are relevant. The major questions, then, relate not to the existence of these components, but rather to their relative contributions to the observed spectra (and variability) from source to source, and, within a given source, as a function of the source luminosity, 'state', and history. Ultimately, our goal is to tie these phenomena to basic system parameters (black hole mass, spin, accretion rate onto the hole, secondary mass, binary separation, etc.), and use them to study General Relativity in the strong field regime [e.g., 28] and plasma physics under extreme conditions.

## THE 'GOLDEN AGE'

As discussed in the abstract above, we are perhaps living in the "Golden Age" of X-ray spectroscopy, with four currently operating instruments that are in many ways complementary to one another. Using various combinations, one can obtain spectra in the 0.1–600 keV regime, (continuous) timing ranging from $\mu$sec to 100's of ksec (and 10's of Msec, if one includes the *RXTE-ASM*), and spectral resolutions as large as $E/\Delta E \approx 1000$. Coordinated multiple X-ray satellite observations are now routinely performed. For example, *RXTE* provides the broad band spectrum while, *Chandra* allows the Fe line region to be decomposed into broad and narrow components [e.g., 29].

In Fig. 3, I show joint *RXTE-INTEGRAL* observations of Cyg X-1 [30], which provides an extremely broad-band spectrum. These particular spectra are very well fit by a low temperature, disk blackbody, Compton upscattered in an $\approx 100$ keV corona with optical depth $\tau_{\rm es} \approx 1$. The spectra are further reflected off of a cold, mildly ionized slab, with reflection fraction $\Omega/2\pi \approx 0.2$. There are plans to follow-up this particular observation in the Fall of 2004 with a multi-observatory campaign (PI: J. Wilms) that will consist of ground based radio and optical, along with simultaneous *XMM-Newton*, *RXTE*, and *INTEGRAL* observations. This will achieve the broadest band spectrum of any GBHC to date.

This highlights a very important point about X-ray spectroscopy as currently practiced: it no longer solely deals with X-ray spectra. Gamma-ray spectra are crucial for constraining high energy cutoffs, which yield coronal temperatures and are likely important for distinguishing between X-ray emission from jets and coronae. Radio spectra constrain models of the jets. IR and optical spectra constrain jet and outer-disk models. All these components are coupled observationally, and hence must be coupled theoretically. One of *RXTE*'s greatest contributions to the study of X-ray spectra of GBHC has been to reveal the coupling of radio and X-ray emission. For example, the low/hard state of GX 339−4 reveals that the X-ray flux, $F_{\rm X}$, is related to the radio flux, $F_{\rm r}$, by $F_{\rm X} \propto F_{\rm r}^{1.4}$ [31]. It further has been suggested that this trend may be universal in the hard state of GBHC [32].

Whether one agrees or disagrees with the X-ray jet model of hard state GBHC [e.g. 27], it is worthwhile noting that prior to the launch of *RXTE*, few would have ever even attempted to apply a model (at least to GBHC, as opposed to AGN) that attempts to describe the spectrum over 9 orders of magnitude in photon energy. The data simply did not exist. The extremely flexible scheduling of *RXTE* has allowed such multi-wavelength observations to be obtained far more readily. Furthermore, such observations have been carried out over multiple flux levels and spectral states[1], allowing the discovery

[1] This points out another unique advantage of *RXTE*. To date, there have been eight *Chandra* observations of Cyg X-1, but over 200 *RXTE*

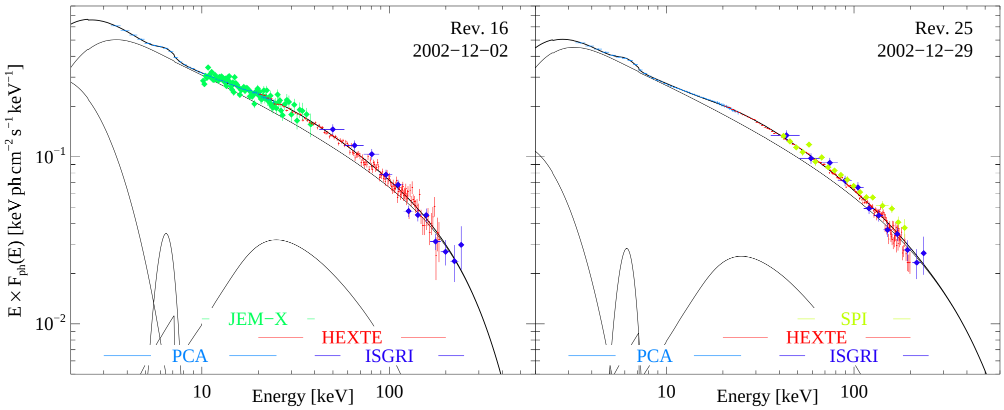


**FIGURE 3.** Simultaneous *RXTE* and *INTEGRAL* observations of Cyg X-1 (Pottschmidt et al. 2003). These are 'unfolded spectra', comprised of a disk component, a broad gaussian line at 6.4 keV, and a power law with exponential cut-off reflected from an ionized slab. In the regions of overlap, there is very good agreement between the *RXTE* instruments (*PCA* and *HEXTE*), and the *INTEGRAL* instruments (*JEM-X* and *HEXTE*).

of spectral correlations as described above [31, 32].

Along with broad-band flux and spectral correlations, current *RXTE* observations have been highlighting correlations of these properties with variability features. In the hard state, flux appears correlated with spectral hardness, which in turn appears correlated with peak frequencies of characteristic broad features in power spectra (PSD) of X-ray variability [e.g. 33, 34, 8] and with the time lags between hard and soft X-ray variability [35, 8, 36]. These properties may further be correlated with 'finer' spectral features, such as reflection fraction [37, 34, 8]. Again, these strong observational couplings indicate that there must be fundamental theoretical underpinnings. X-ray spectroscopy is (or at least, should be) inseparable from X-ray variability studies.

## LOOKING FORWARD

*Greetings, my friends. We are all interested in the future, for that is where you and I are going to spend the rest of our lives. And remember, my friends, future events such as these will affect you, in the future. – Criswell, 'Plan 9 From Outer Space'*

### The Glass is (Mostly) Full

Where do we go from here, and are we well-prepared to get there? In the short-term, over the next two years, I believe that the answer is an emphatic yes. We will not see any of our capabilities diminish (barring any unforeseen events that affect currently operating satellites), and we will see some very important new capabilities emerge. One of these capabilities that I personally am most excited about is the advent of new IR and optical observations of GBHC. Although the discovery of microquasars is nearly a decade old, dedicated radio/X-ray spectral campaigns are less than seven years old. The correlation of these properties with X-ray timing properties is even more recent. Extending such studies to the IR and optical regimes is likely to be very important.

I foresee this progressing in two ways, both of which are underway now. First, there are dedicated, frequent optical observations of GBHC with small telescopes, such as recent optical observations of XTE J1550−564 [38]. Such observations can be correlated with the daily monitoring by the *RXTE-ASM*, which will likely shed further light on the nature of GBHC state transitions. IR/optical studies can also provide needed information about the transitions from the radio (jet?) to the X-ray (corona?) part of the spectrum. Specifically, we only have limited observational knowledge of the IR turnover between these two spectral regimes [although see 39].

Second, the twenty year old suggestion that inner-disk flares create optical synchrotron emission [17] was based upon only 100 seconds worth of data, where it was unclear whether the optical led or trailed, or was correlated or anti-correlated [16]! Observations with large modern telescopes with fast photometry systems, such as the *VLT*, have dramatically improved this situation. Very exciting examples are the recent optical/X-ray observations of XTE J1118+480, where possibly correlated optical and X-ray quasi-periodic oscillations (QPO) are observed, and where it was further suggested that the optical variability traces a synchrotron component of the spectrum [40]. Compared to correlated radio/X-ray

observations. If a single observation allows one to study 'weather', *RXTE* has allowed us to study GBHC 'climates'.

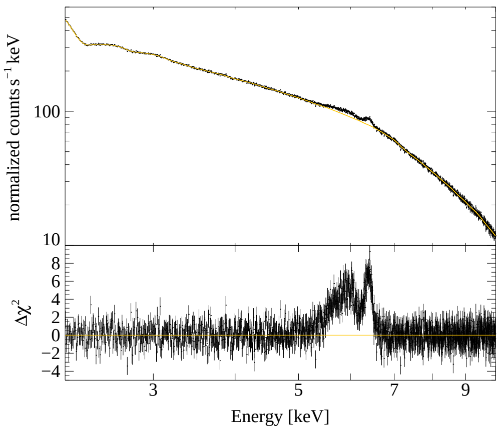


**FIGURE 4.** To a limited extent, *XMM-Newton* has the potential for replacing *RXTE* for studies of X-ray spectral-temporal correlations. Shown here is a simulation of the Cyg X-1 hard state spectrum observed in a proposed modification of the *XMM-Newton* "timing mode" (Wilms et al., in prep.). The simulated spectrum is a reflected power law, plus broad and narrow Fe line components, absent from the fit, with residuals shown above.

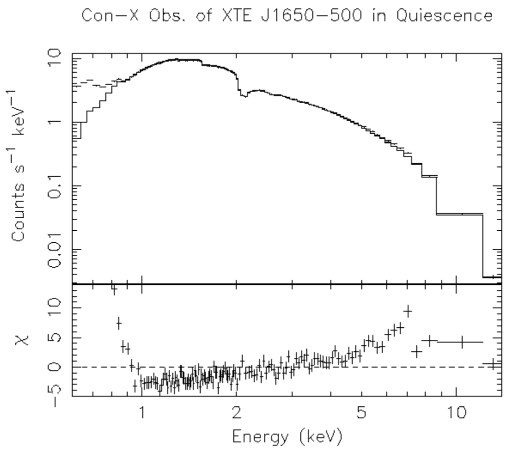


**FIGURE 5.** A simulated 50 ksec *Constellation-X* observation of a quiescent black hole binary, such as XTE J1650-500. The simulated model is a disk component, reflected power law, and broad line, but only the power law has been fit. Residuals clearly reveal the disk and broad line components of the spectrum.

spectral-temporal studies, these optical/X-ray studies are only in their infancy. Again, however, they do rely on the future availability of a flexible, easily scheduled X-ray observatory.

Spectral-temporal X-ray studies will undoubtedly continue in the near term, especially with *RXTE*. But what about the post-*RXTE* era? *Chandra* and the imminent *Astro E II* have somewhat reduced effective areas compared to *RXTE*, as well as potential problems with photon pile-up [e.g., 41] for sources as bright as many GBHC. *XMM-Newton*, although having good effective area, CCD resolution, and reasonably fast timing capability, has suffered from telemetry constraints for bright sources[2]. A potential work-around for this situation may offer the possibility of dramatically improving the utility of *XMM-Newton* for GBHC spectral-temporal studies (Wilms et al., in prep.). In a suggested new mode, the lower energy threshold will be raised to $\approx 2$ keV, thereby reducing telemetry and allowing the use of 'timing mode'. If successful, this will allow *RXTE*-like timing with CCD spectral resolution (see Fig. 4 for a spectral simulation of Cyg X-1; courtesy J. Wilms). However, *XMM-Newton* still has fairly severe scheduling constraints, and such a new mode will not be effective for GBHC much brighter than Cyg X-1 (which numerous X-ray novae in outburst are).

[2] This has often required the use of the 'burst mode' for bright GBHC, wherein only $\approx 3\%$ of the photons are telemetered to ground.

Regardless of the success of this proposed modified mode, in the near term *XMM-Newton* and *Chandra* both will further our understanding of the X-ray spectra, and variability, of quiescent GBHC. (This is provided that these objects are studied with sufficiently long integration times; short observations are often limited to simple spectra, e.g. constrained power laws, and flux measurements.) One interesting recent GBHC observation is of the quiescent state of XTE J1650−500 [42]. The observed spectrum was hard, as is typical for 'low/hard state' GBHC. Furthermore, the X-ray variability revealed a break in the power spectrum at very low frequency, consistent with previously observed trends for the characteristic PSD frequencies of hard state GBHC to decrease with decreasing flux. This is the first claim that this trend continues into such extremely faint states.

This is one area where the farther future offers substantially greater promise. Current studies are limited by photon statistics of such faint sources. (For a given signal-to-noise, the required integration times for PSD studies scale as received count rate squared; see [43].) An important attribute of *Constellation-X* (as well as *XEUS*, although here I do not show simulations of this latter mission) is that with its proposed very large effective area, we simultaneously will obtain detailed X-ray spectral and variability data from extremely faint sources. As an example, in Fig. 5 I present a simulation of a 50 ksec observation of a quiescent GBHC, such as XTE J1650−500. Instead of simple power-law spectrum, I have included a disk blackbody and relativistic line, which are clearly revealed in the residual spectra

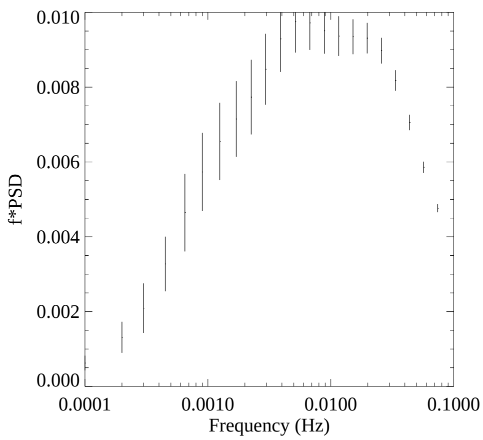


**FIGURE 6.** Simulated 50 ksec *Constellation-X* observation of the X-ray variability power spectrum (shown as frequency × amplitude) possibly associated with the quiescent X-ray spectrum shown in Fig. 5. (Power spectrum amplitude and frequency extrapolated from *Chandra* observations of XTE J1650−500 in quiescence; Tomsick, Kalemci, & Kaaret 2003.)

when only fitting a power law[3]

In addition to revealing structure in the spectrum, *Constellation-X* observations potentially could measure structure in the PSD of the X-ray variability. Fig. 6 shows a simulated PSD that may be associated with the spectrum of Fig. 5. (The variability parameters are modeled after the observations presented in [42].) Thus, by correlating such spectral features as the presence of a soft disk component or broad line with characteristic variability features, we may determine whether these properties truly are associated, for example, with a varying 'transition radius' between an outer thin disk and an inner corona [see the reviews of 1, 2, and references therein].

## The Glass is (a Little) Empty

As sketched out above, I am very optimistic about current progress in the field, and about some of the new directions that the field seems to be taking. But is there anything missing from our spectroscopic capabilities in the future? And is there room for a replacement for *RXTE*? My own opinion is that the answer to both questions is 'yes'. Two of my major concerns for the future have been alluded to above. The first is that we have become quite attached to the flexibility, ease of scheduling, and the — still, in comparison to other X-ray satellites — rapid maneuverability of *RXTE*, yet we have no designated replacement.

The *Swift* X-ray/gamma-ray satellite will of course be flexible, rapidly maneuverable, and have broad energy coverage with good timing capabilities. Understandably, however, the majority of its program will be devoted to its gamma-ray burst program, and we cannot reasonably expect it to supplant the current radio/optical/X-ray multi-wavelength spectral programs conducted by *RXTE*. To a limited extent, *Swift* also will act as a replacement for the *RXTE-ASM*. Again, however, this replacement will be incomplete. The eventual loss of the *ASM* will impact future *XMM-Newton* and *Chandra* observations in several ways.

Not only will we no longer have a soft X-ray trigger for scheduling pointed spectral observations of rare events, but we will also no longer have a long term lightcurve to act as context for pointed observations by other instruments. As alluded to above, the number of *XMM-Newton* or *Chandra* observations of any given GBHC is usually quite limited in comparison to available *RXTE* observations. Currently, these more limited observations can be compared to spectral properties revealed by the *ASM*, which in turn often can be compared to more detailed pointed *RXTE* observations of the same source at an earlier time with similar *ASM* spectral characteristics. (Currently, many radio/optical/X-ray studies are conducted as monitoring programs utilizing the *ASM*, e.g., [38, 39].) We very well may lose this ability well before the end of the mission lifetime of either *XMM-Newton* or *Chandra*.

The second concern that I have for future X-ray spectral studies is that we may be forgoing opportunities to delve deeper into studies of spectral-temporal correlations. Further progress is partly contingent upon having the ability to study rapid variability with a large effective area instrument. Specifically, the ability to study X-ray variability *phase information* and *coherence* is severely limited by photon statistics, even more so than are PSD studies [43, 44].

One currently utilized method of studying spectral-temporal correlations is the so-called 'Fourier resolved spectroscopy' [34, 45] (although this technique has been previously applied to *Ginga* observations of GBHC). Essentially, it involves weighting a spectrum by a PSD amplitude. One of my major objections to such techniques is that they ignore phase information. For example, a pivoting power law appears as a broken spectrum, with the break at the pivot. Or another way of phrasing it, we are taking knowledge from an incoherent sum (the PSD), and applying that to something which is likely comprised of (quasi-)coherently added components (the spectrum). Techniques that go from the spectrum to an incoherently summed PSD seem to me more promising.

[3] This simulation and figure are modeled after a similar presentation by Jon Miller at the Constellation-X Workshop held at Columbia University, May 2003.

Such thoughts, as with many of the theories discussed in the introduction, are of course not new, and have been contemplated for prior X-ray observations of GBHC. For example, using *Ginga* data, Miyamoto and collaborators hypothesized that GBHC variability was comprised of 'disk' and 'coronal' components incoherently summed [46]. By first fitting the spectral component and then using the normalizations of the disk and coronal portions of the spectrum, they found that a fair representation of the associated PSD could be obtained. An incoherent sum for the variability, however, is just the first approximation. Each component likely has its own phase (or, equivalently, lag between hard and soft variability) that can add/interfere in the regions of strong overlap of the PSD components.

A potential example of such effects is shown in Fig. 7. These PSD, phase lags, and coherence (i.e., normalized amplitude of the cross-correlation; [44]) are composed from a set of (very similar) observations of GX 339−4 [47]. The PSD is well modeled as a sum of broad features. It is possible that *each* of these broad features has its own intrinsic phase/time lag between hard and soft variability (a hypothesized decomposition is shown in Fig. 7), and that the net observed phase lag is the sum of these components. Furthermore, one would expect drops in the coherence (i.e., the degree of linear correlation between soft and hard variability) in regions where the independent PSD components overlap [see Fig. 7, and 47]. (Again, these thoughts are not new, and have been considered by Miyamoto and collaborators for *Ginga* data of GBHC; [48].)

Again, I believe the most fruitful avenue of research to pursue is to start with a spectral decomposition and then work forward towards the timing attributes, specifically, PSD, phase, and coherence. A very good example of this approach is the work by Poutanen and Gierlinski [49, and these proceedings], who modeled the X-ray spectra and variability of the pulsar SAX J1808.4−3658. One of their key results was to show that the measured phase could be related to the individual spectral components. This particular source, however, had the advantage of being relatively bright and having a strong variability feature (i.e., the pulse). Thus there were good statistics for performing such a spectral-temporal decomposition. But what about GBHC where most variability features are broad?

This latter case is difficult because obtaining variability phase information requires extremely good statistics, and hence large effective areas. (Whereas there is an 'optimal filter' to remove many effects of Poisson noise from the PSD, there is no optimal filter to minimize noise effects on phase measurements; [43, 44].) This seems to me a prime goal for 'spectral-temporal' studies that could be performed by a successor to *RXTE*. Also, given sufficient detector area *and* the ability to spectrally decompose rapid variability, we may yet consider performing spectral-temporal studies in the time domain (as opposed to the Fourier frequency domain). It is worthwhile noting that, although *Constellation-X* is partly being designed with the goal of 'reverberation mapping' of the broad Fe line in AGN [50], a similar study in GBHC not only requires a faster time response, but also larger effective area. The obtained signal-to-noise in a spectrum integrated over a characteristic time scale (viscous, thermal, or dynamical) is actually greater for AGN compared to GBHC [see the discussion of 2, and references therein]. Again, this suggests a successor mission to *RXTE* with its rapid timing capabilities, but substantially larger effective area.

## SUMMARY

Over the past 30 years, we certainly have come a long way in our understanding of the spectra (at all wavelength bands, not just X-ray) of Galactic black hole binaries. Although many of the components of our theories and models have been in existence for a large fraction of this history, it truly is the modern era, with four unique and complementary X-ray satellites, working in cooperation with other wavelength bands, wherein we are able to conduct careful tests of these concepts. Our capabilities will increase further (with the launch of *Swift* and *Astro E II*, and the continuing missions of current satellites) in the short-term future. The farther future promises more ambitious instruments, i.e., *Constellation-X*, *XEUS*, and *MAXIM*, which will greatly enhance our knowledge of X-ray spectra.

Still, if there is any cause for wistfulness, it will be the eventual loss of the *RXTE* pointed instruments, *PCA* and *HEXTE*, and the *RXTE All Sky Monitor*. The flexibility of *RXTE* has been crucial for multiwavelength spectroscopy, and it has reinvigorated the study of spectral-temporal correlations. If there is a 'hole' to be filled in our, otherwise very exciting, future studies of X-ray spectra, it is a new flexible satellite with rapid timing capabilities and effective area larger than *RXTE*.

## ACKNOWLEDGMENTS

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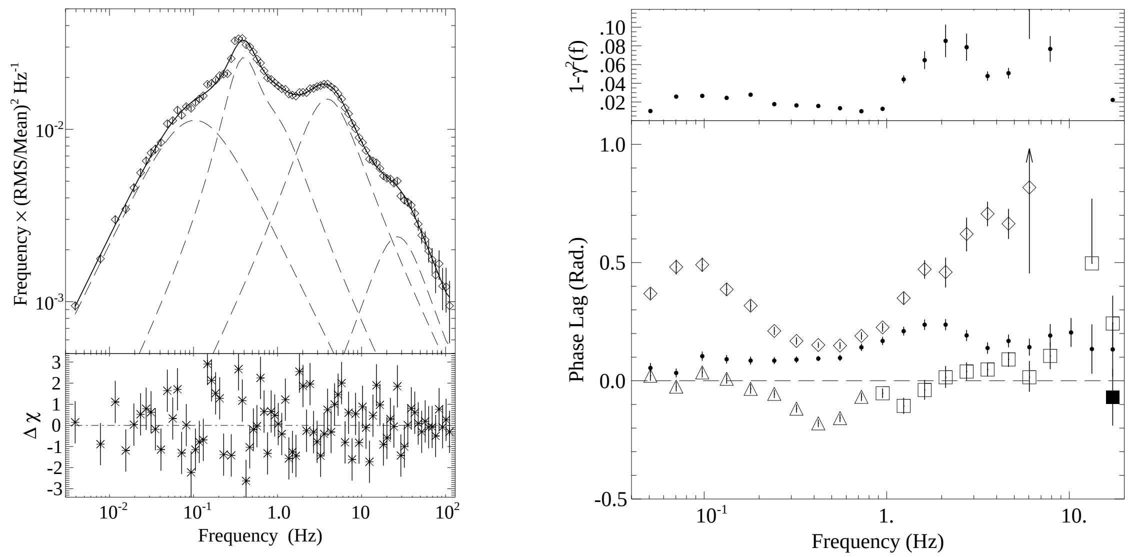


**FIGURE 7.** A composite power spectrum (presented as frequency × power) of GX 339−4 in its hard state (left), along with the associated phase lags (right bottom) between hard and soft X-ray variability, and the coherence (presented as one minus coherence) of the phase lags (right top). For the lag and coherence, filled circles are the data, while the clear triangles, diamonds, squares, and filled square are a possible decomposition of the lag into individual and independent components associated with each 'broad feature' in the PSD (Nowak 2000).

ject of a more thorough review by someone more knowledgeable than myself. This work has been supported by NASA grants NAS8-01129 and GO3-4050B.

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